Self-consistent continuum random phase approximation calculations of ^{4}He electromagnetic responses

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We study the electromagnetic responses of ^{4}He within the framework of the self-consistent continuum random phase approximation theory. In this approach the ground state properties are described by a Hartree-Fock calculation. The single particle basis constructed in this manner is used in the calculations of the continuum responses of the system. Finite-range interactions are considered in the calculations. We compare our results with photon absorption cross sections and electron scattering quasi-elastic data. From this comparison, and also from the comparison with the results of microscopic calculations, we deduce that our approach describes well the continuum excitation.

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One of the crucial ingredients in the description of the nuclear excitation in the continuum is the re-interaction between the emitted nucleon, and the remaining nucleus. The continuum random phase approximation (CRPA) theory describes this effect, commonly called final state interaction (FSI), as linear combination of particle-hole and hole-particle excitations. Recently, we have developed a technique to solve CRPA equations with finite-range interactions by considering, without approximations, the excitation to the continuum [1]. The application of our approach to medium-heavy nuclei produces satisfactory descriptions of the experimental data. The positions of the peaks in the excitation of the electromagnetic giant dipole and quadrupole resonances are well reproduced, even though the widths of the resonances are too narrow and their heights too high. There are strong indications that these problems are related to the hypotheses underlying the RPA theory which is limited to consider one-particle one-hole excitations only [2].

In this article, we study the ability of our CRPA calculations to describe the electromagnetic responses of the ^{4}He nucleus. The application of the CRPA approach to the ^{4}He nucleus is quite unusual, since the number of particles composing the system is too small to consider the mean-field hypotheses, on which the RPA theory is based, to be reliable. On the other hand, for the ^{4}He nucleus we have the possibility of comparing our results with those of a fully microscopic approach, based on the Lorentz Inverse Transform (LIT). This approach uses nucleon-nucleon interactions constructed to describe the two-nucleon systems and solves the Schrödinger equation without approximations, contrary to the CRPA, which is an effective theory where the many-body effects are considered by changing the parameters of the interaction.

We have constructed the single particle basis by doing Hartree-Fock calculations. We tested the validity of our description of the ^{4}He ground state, by using three effective interactions: two different parameterizations of the Gogny interaction, the more traditional D1S [3] interaction and the more modern D1M force [4], which produces a reasonable neutron matter equation of state, and an old finite-range effective interaction constructed to reproduce at best the ^{4}He binding energy, the B1 interaction of Brink and Boeker [5].

While the D1S and D1M interactions have been widely used in the literature to study the properties of medium-heavy nuclei, the applications of the B1 interaction have been limited to the ^{4}He and to some test case for microscopic many-body calculations, since this interaction has a soft core short-range repulsion in the scalar channels. The properties of these two types of interactions are rather different. For example, the D1S and D1M interactions reproduce the empirical values of saturation density and binding energy per nucleon of symmetric nuclear matter, while the symmetric nuclear matter equation of state of the B1 interaction saturates at 0.21 fm^{-3} with the energy per nucleon of -15.7 MeV. Also the values of the symmetry energies, strictly related to the position of the peak of the isovector dipole resonance, are rather different. For the D1M and D1S interactions we obtain respectively the values of 29.45 MeV and 31.77 MeV, in general agreement with the commonly accepted empirical values included in the ranges from 30 to 35 MeV. For the B1 interaction we obtain the value of 58.55 MeV.

	binding energy	separation energies protons	neutrons	rms
D1S	30.28	19.39	20.09	2.04
D1M	29.54	18.25	18.96	2.02
B1	28.48	26.00	26.00	1.92
exp	28.29	19.81	20.58	1.68

Table I: Binding energies, proton and neutron separation energies, in MeV, and rms charge radii, in fm, obtained for the three different interactions considered in this work. The experimental values are taken from Refs. [6, 7].

The binding energies and the proton and neutron separation energies obtained by using the three different interactions are given in Table I. The experimental values have been taken from the compilations of Refs. [6, 7]. The performances of the HF theory in the description of the ^{4}He ground state properties are quite unsatisfactory. The values of the binding energies generated by the two Gogny interactions are too large with respect to the experimental value. By construction, the B1 interaction makes a better job in this case. The situation is reversed when the proton and neutron separation energies are considered. In this case, the two Gogny interactions provide a better description than the B1 force.

We compare in Fig. 1(a) our charge distributions with the empirical one [8]. The discrepancies are remarkable especially if compared with the good description of the charge distributions of medium-heavy nuclei obtained by using the D1M and D1S interactions [1]. In the present case, the charge distributions are more extended than the experimental one as it is also indicated by the values of the root mean squared (rms) charge radii compared in Table I. We complete the information about the charge density distributions by comparing in Fig. 1(b) the elastic form factors obtained with these charge densities with the experimental data of Refs. [9–12]. The theoretical charge densities are larger than the empirical one and produce form factors which narrower than the experimental one.

The results we have just presented confirm the difficulties of the mean-field model in producing a good description of the ^{4}He ground state properties. In any case, we are interested in investigating the capacity of our self-consistent approach to describe the excitation of the ^{4}He nucleus in the continuum.

As a first test of the CRPA results we have calculated the total photoabsorption cross section by using the method described in detail in Ref. [1] where it has been applied to some oxygen and calcium isotopes. We compare in Fig. 2

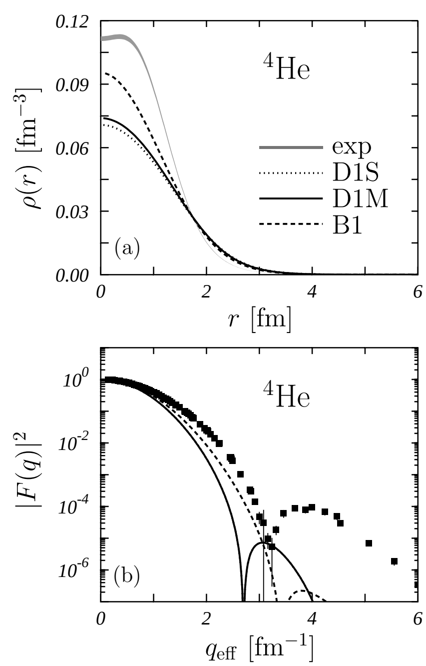

Figure 1: (color on line). Panel(a): charge density distributions calculated with the D1S (dotted line) and D1M (solid line) parameterizations of the Gogny interaction and with the B1 interaction (dashed-dotted line) compared to the empirical density taken from Ref. [8]. Panel (b): form factors obtained with the charge distributions of the upper panel. The experimental data are rom Refs. [9–12].

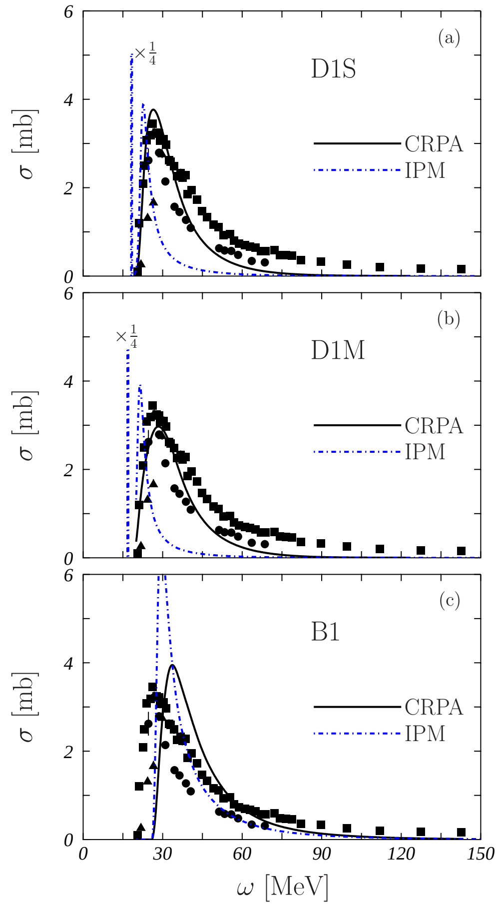

Figure 2: Total photoabsorption cross sections obtained with the three interactions used in this work. The full lines show the results of the self-consistent CRPA calculations and the dashed-dotted lines show the IPM results based on the HF calculations done with the various interactions. The experimental data are from Refs. [13] (squares), [14] (triangles) and [15] (circles).

our results with the available experimental data [13–15]. We have obtained the total cross section by summing the contribution of the 1^- and of the 2^+ excitations which contributes to the total cross section only for about the 2%. Panels (a), (b) and (c) show the results obtained with the D1S, D1M and B1 interactions, respectively. With the dashed-dotted lines we show the results of the independent particle model (IPM) calculation, i.e. those obtained by switching off the residual interaction in the CRPA calculation. The solid lines show the CRPA results.

The resonance is dominated by the transition of both protons and neutrons from the $1s_{1/2}$ state to the p waves, both $p_{3/2}$ and $p_{1/2}$. The IPM results indicate the resonances of these two partial waves. In the D1S and D1M calculations the $1p_{3/2}$ state is bound, while the $p_{1/2}$ state is in the continuum. In the figure, the bound responses for these two calculations, represented by the narrow vertical lines in the panels (a) and (b) around 18 MeV, have been multiplied by a 1/4 factor. In the calculations with the B1 interaction only the $1s_{1/2}$ states are bound, and already the IPM generates a peak of the resonance at energies higher than that of the experimental peak. The inclusion of the residual interaction generates an additional shift at even higher energies. In general, the residual interaction shifts the IPM responses to higher energies, since the 1^- resonance is an isovector excitation.

The direct comparison between our CRPA results, the experimental data and the results of of the microscopic calculation of Refs. [16] (dashed curve) based on the LIT technique is done in Fig. 3. This figure emphasizes the poor performances of the B1 interaction in reproducing the experimental data. This result confirms the indication already given by the large value of the nuclear matter symmetry energy: the isospin part of the B1 interaction is too strong. More interesting is agreement between the results obtained with the D1S and D1M interactions and those of the microscopic calculation is remarkable. The peaks of the resonances generated by the three calculations are in the same position. In the peak, the D1M cross section has a better agreement with the LIT result with respect to the D1S one. This seems to indicate that the modifications of the parameters aimed to produce a reasonable neutron matter equation of state improved the description of the isospin channels of the interaction. In any case these differences are within the uncertainties of the input of the RPA calculations and not related to method itself. For this reason

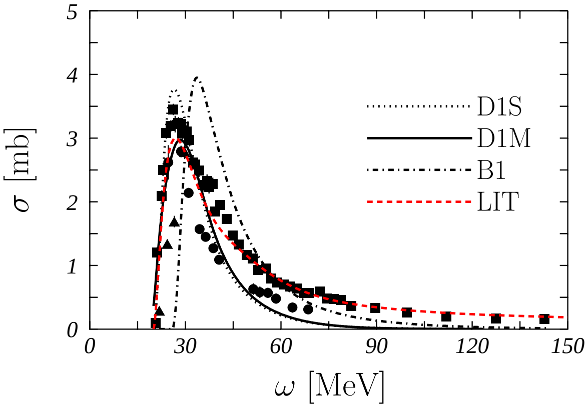

Figure 3: Comparison of the total photoabsorption cross sections obtained in the self-consistent CRPA calculations with the LIT results of Ref. [16]. The experimental data are from Refs. [13–15].

we perfom calculations with different interactions. We find more interesting the general differences between our RPA results and those of the LIT. The results of our calculations drop more quickly in the high energy tail. Even though the experimental situation is still quite controversial, the microscopic calculations seem to give a better description of the data.It is worth to remark that, in our computational scheme [1], ground state properties, single particle energies and wave functions and CRPA responses are stricly related by the use of the same effective nucleon-nucleon interaction.

We have tested the relevance of a good description of the charge density distribution in the evaluation of 1^- excitation by using single particle wave functions generated by a Woods-Saxon potential whose parameters have been properly chosen. The calculations have been done within a discretize RPA model, and compared with the analog self-consistent calculations done with HF wave functions. The response strongly depends on the effective interaction, and no sensitive improvement with respect to the self-consistent approach has been found.

We used our computational scheme to calculate the quasi-elastic electron scattering responses. In these calculations we used the one-body electromagnetic currents and the nucleonic electromagnetic form factors described in Ref. [17]. We have done calculations with all the three interactions mentioned before. However, since the results are rather similar, we present in Fig. 4 only those results obtained with the D1M interaction.

The calculations of the quasi-elastic responses have been done by summing the contribution of all the electric and magnetic multipole excitations up to numerical convergence was reached. This has been achieved by considering multipole excitations up to angular momentum $J = 6$ for the results at momentum transfer value $q = 200$ MeV/c, and up to $J = 8$ for $q = 500$ MeV/c. In our calculations we have considered only one-body electromagnetic currents.

In Fig. 4 the results of the CRPA calculations are indicated by the full lines, while with the dashed-dotted curves we show the IPM results. We have performed also calculations were the FSI has been totally switched off, that is, we have calculated the responses in IPM and we have substituted the mean-field wave functions of the emitted nucleon with plane waves. We have indicated as plane wave impulse approximation (PWIA) these results and we present them by using dotted lines. The dashed lines indicate the LIT results of Refs. [18–20]. The data for q=200 MeV/c are those of Ref. [21], while for the other values of the momentum transfer the black squares indicate the data of Ref. [22] and the white circles those of Ref. [23].

We observe first that the agreement between the CRPA results and the experimental data is quite good for all the values of the momentum transfer considered in the case of the longitudinal responses (left panels). This confirms the results of the photoabsorption cross section. In the case of the transverse response, our results slightly underestimate the data. In our calculations we did not consider the meson-exchange-currents which enhance the transverse response [24, 25].

A second point is that CRPA effects become smaller with increasing value of the momentum transfer in the longitudinal response. This can be seen by comparing the CRPA results with those of the IPM. The full and dashed-dotted lines are quite different for 200 and 300 MeV/c, but they become closer at 400 MeV/c, and almost overlap at 500 MeV/c.

Transverse responses are more sensitive to the presence of CRPA correlations. The differences with the IPM results grow slightly with the momentum transfer. On the other hand, the comparison with the PWIA results, the dotted lines, indicates that the mean field is taking into account a large part of FSI for all the momentum transfer values considered. It is interesting to remark again the good agreement between our CRPA results and those obtained with the fully microscopic calculations done with the LIT technique, shown by dashed lines.

While the HF theory gives a poor description of the ^{4}He ground state, the self-consistent CRPA theory describes well the excitation of the continuum, for both photoabsorption and quasi-elastic inclusive electron scattering data. We

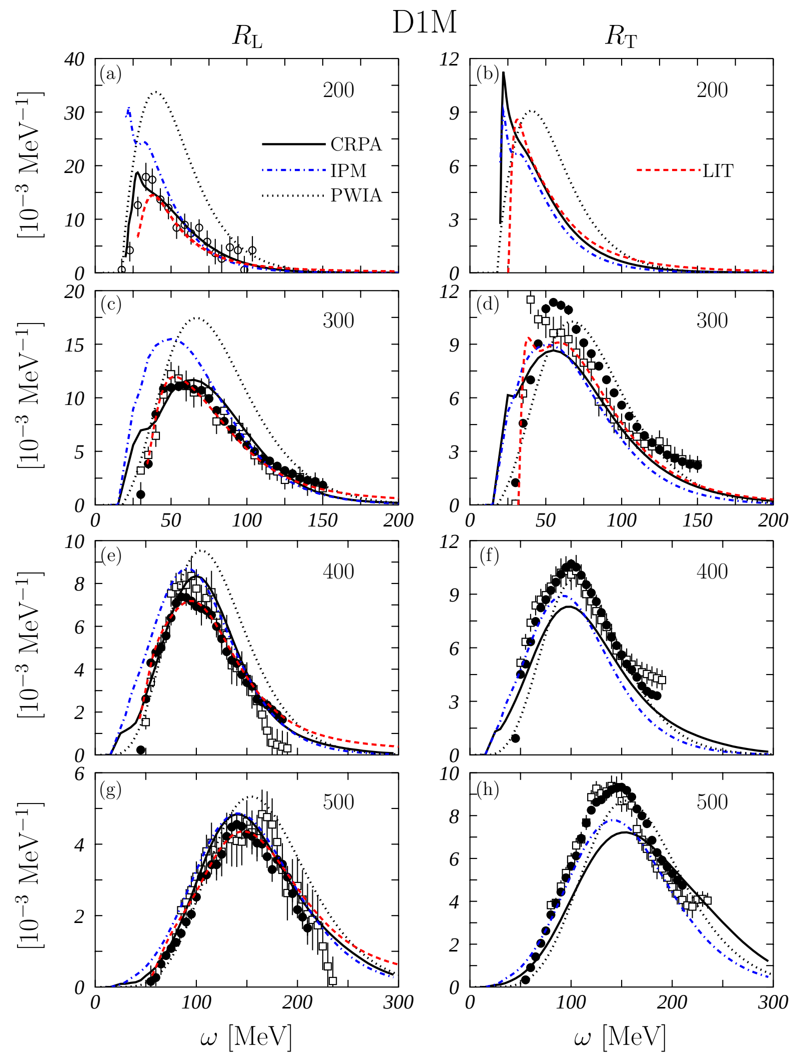

Figure 4: Comparison of the longitudinal (left panels) and transverse (right panels) quasi-elastic electron scattering responses obtained with the D1M interaction within the CRPA (solid curves), IPM (dashed-dotted curves) and PWIA (dotted curves) frameworks, with the LIT microscopic results of Ref. [18–20] (dashed curves). The labels in the panels indicate the values of the momentum transfer in MeV/c. The experimental data for momentum transfer of 200 MeV/c (open circles) are taken from Ref. [21] while those shown in the other panels are taken from Ref. [22] (open squares) and from Ref. [23] (solid circles).

may say that our CRPA calculations are able to describe well the FSI between the emitted nucleon and the remaining nucleus. This good description of the FSI is obtained for a wide range of values of the momentum transfer.

It is surprising that the performances of the CRPA are superior in ^{4}He than in medium-heavy nuclei, where the theory is supposed to be tailored. In medium-heavy nuclei a spreading width should be added to have reasonable description of the excitation data in the continuum. As it is shown in Ref. [1], the difficulties of the CRPA in describing the responses of medium-heavy nuclei are due to the fact that excitations more complex than one-particle one-hole are not considered. The effects of these excitations are almost absent in ^{4}He, and for this reason the CRPA works very well in this case.

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